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Vol. III

MTR-118
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COLD LAKE RADIO PROPAGATION AND METEOROLOGICAL EXPERIMENT

(in Three Volumes)

Volume III

Description of the Vertical Reflection Interferometer

and the Measurement Accuracy

AUGUST 1967

F/L G.A. Fatum (RCAF)
B. J. Starkey (EMI-Cossor, Ltd., Canada)

Prepared for

DEPUTY FOR SURVEILLANCE AND CONTROL SYSTEMS
AEROSPACE INSTRUMENTATION PROGRAM OFFICE
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

Project 7010
Prepared by
THE MITRE CORPORATION
Bedford, Massachusetts
Contract AF19(628)-5165

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FOREWORD

The work reported in the three volumes of this report was supported by the Electronic Systems Division of the Air Force Systems Command, L. G. Hanscom Field, Bedford, Massachusetts, through the MITRE Corporation's Technical Objectives and Plans 7010 - Environmental Factors - under Contracts AF 19(628)-2390 and AF 19(628)-5165.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

James F. Shunk
for OTIS R. HILL, Colonel, USAF
Director of Aerospace Instrumentation
Program Office

ABSTRACT

A radio reflection interferometer was used to determine effective earth's radii values from the observation of multipath fading records and corresponding signal source positions. Received signal levels, master timing codes, and signal source range were automatically recorded in digital and analog format. Signal source height was obtained from radar altimeter and phototheodolite records.

The digital and analog data were processed in an IBM 7094 to obtain extremely accurate calculations of the propagation parameters.

ACKNOWLEDGEMENT

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The participating members in the experiments were designated "The Multipath Propagation Panel" of the above, larger Joint Group. The authors wish to acknowledge the cooperation and coordination provided through the Joint International Group and presently represented by the Canadian and United States cochairmen:

Wing Commander I. Gillean
Director of Electronic Warfare
Canadian Forces Headquarters
Ottawa, Ontario

Mr. R. Creamer
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The Cold Lake Radio Propagation and Meteorological Experiment is reported in three volumes:

Vol. I - Description of a Radio-Meteorological Experiment to Measure Ray-Path Bending in the Troposphere with a Vertical Interferometer

Vol. II - Determination of Radio Propagation Conditions from Interferometer and Lake Surface Measurements

Vol. III - Description of the Vertical Reflection Interferometer and the Measurement Accuracy

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SECTION I

INSTRUMENTATION

INTRODUCTION

Volume I of this report (MTR-118) describes the use of a vertical reflection interferometer to measure ray-path bending in the troposphere in an experiment carried out at the Primrose Lake Evaluation Range (PLER), Cold Lake, Alberta, Canada.

This volume (3) describes the particular instrumentation used to transmit and receive radio signals as well as the methods used to obtain accurate transmitter range and height relative to the fading times of the received signals. Amplitude characteristics of these signals are presented in their entirety in Volume I. However, the entire printouts of a computer, including amplitude, range, time, and effective bending parameters, are too extensive to be included in this document; these data will be retained by The MITRE Corporation for future reference.

TRANSMITTER

An RCAF North Star aircraft from the Central Experimental and Proving Establishment (CEPE) at Uplands, Ottawa, was employed as the single-source vehicle. Wideband (about 30 MHz) noise-modulated

transmitters provided power sources on L- and S-bands with outputs of 800 and 400 watts respectively.

The L-band antenna pattern was essentially omnidirectional, whereas the S-band horizontally polarized antenna had an average front-to-back ratio of about 8 db.

For the experiment to be successful, positional data (altitude and range) of the signal-source aircraft had to be measured accurately and with precise timing relative to data recorded at the ground receiver. The most difficult parameter to measure was aircraft altitude; therefore, to assist in this measurement, the aircraft track was selected to pass over several large lakes, and the pilot flew a constant pressure-altimeter course, with the true height established from radar-altimeter readings taken over Cold Lake at the beginning of each outbound leg. The SCR 718 radar altimeter readings were recorded thereafter at 20-second intervals when the aircraft overflew the other lakes, along its path. In this way an attempt was made to obtain true altitude data which could be referred to the Cold Lake reflection-surface level. These readings provided the majority of the data used in determination of aircraft height, as detailed in Section II.

In an attempt to obtain additional aircraft-altitude information, a KS4 Aerograph System was installed. This provided analog recordings

of the pressure altitude, air temperature, air speed, and relative humidity. One-minute time marks were applied to these recordings from a Bulova Accutron clock.

The Distance Measuring Equipment (DME) at the ground receiver was the primary method of measuring the slant range between the signal-source aircraft and the receiver. This system utilized the standard APX-25 SIF transponder normally carried by the aircraft.

As a backup for the DME, the aircraft navigator inserted event marks on an oscillograph recording as the aircraft passed over clearly defined landmarks, such as the shore lines of the various large lakes along the track, as observed through the gyro-stabilized drift sight. The central time transmissions from PLER were received on VHF and applied to the same recorder to provide the necessary precise time correlation. The accuracy of this system depended to a great extent on the accuracy of the terrain survey, which, in this area, was somewhat doubtful.

GROUND INSTRUMENTATION

The ground receiving equipment used in the trials consisted of the Canadian-built Electronic Countermeasures Field Strength Monitor Van, which is, basically, a microwave receiving-recording system installed in a semitrailer.

The primary power requirements (220 volts, three phase, 60 cycles, at 20 amperes per phase) may be provided by commercial power or by a mobile power unit which consists of twin diesel-generator sets mounted in a truck. The semitrailer and power truck are shown in Figure 1.

The receiver is capable of operating at L-band (1000-1500 MHz) S-band (2600-4000 MHz), and X-band (8500-10, 500 MHz). Only one frequency band may be used at a time. A block diagram of the instrumentation is shown in Figure 2.

Standard-gain horn antennas are available for each of the three frequency bands. They may be mounted to receive either horizontally or vertically polarized signals and were remotely steerable in azimuth and elevation.

MICROWAVE RECEIVER

Broadband low-noise and medium-power traveling wave tubes (TWT) are used in cascade amplification on L- and S-bands to drive a Polarad receiver. A minimum detectable signal (MDS) of -110 dbm at a noise figure of 10 db is normal. On X-band, a tunnel-diode amplifier precedes the low-noise TWT to provide an MDS of -115 dbm at a noise figure of 8 db. On each band, a high-power TWT drives a thermistor and a power meter to give a measure of the total power being received

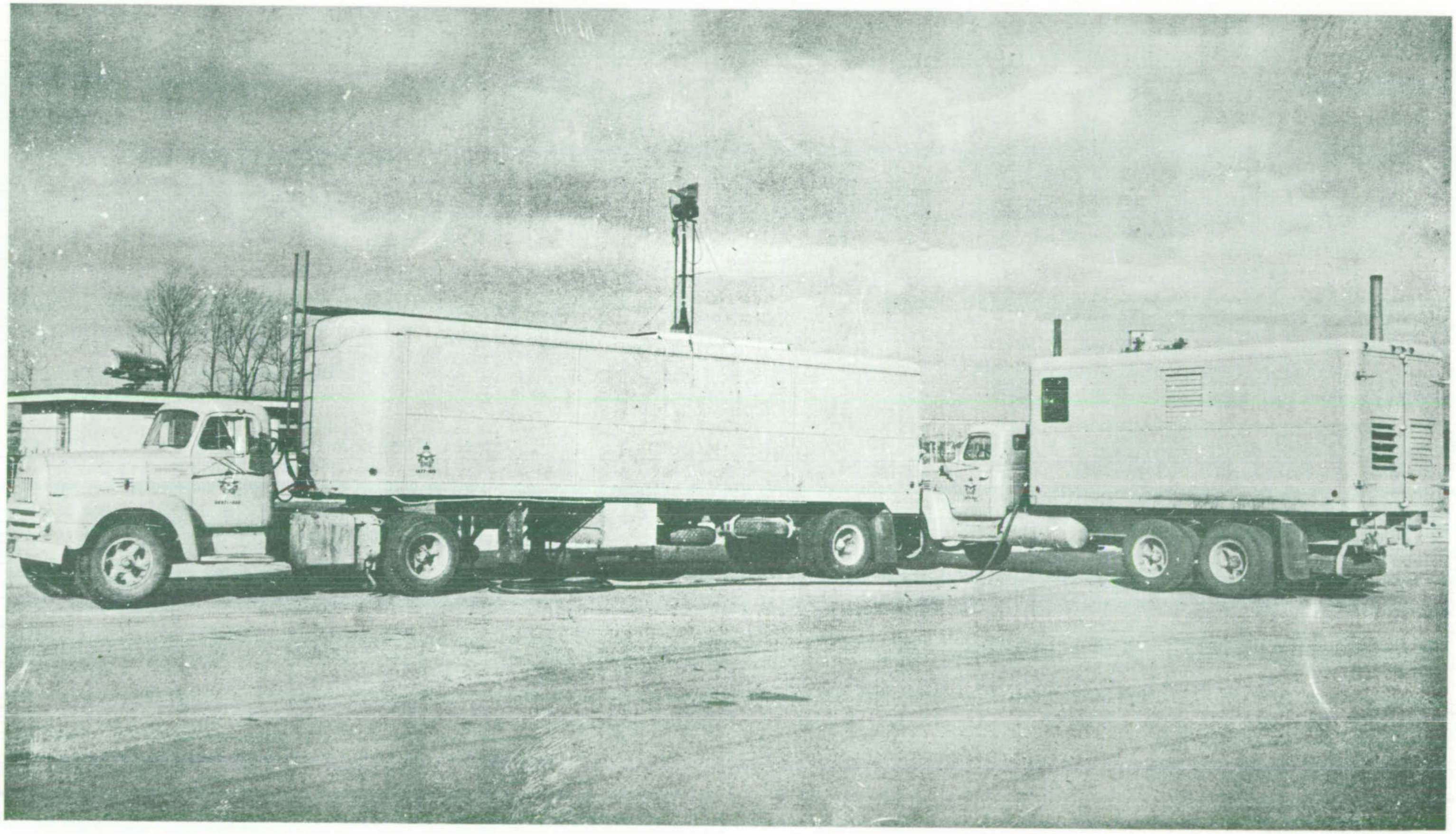

Figure 1. Semi-trailer and Power Truck

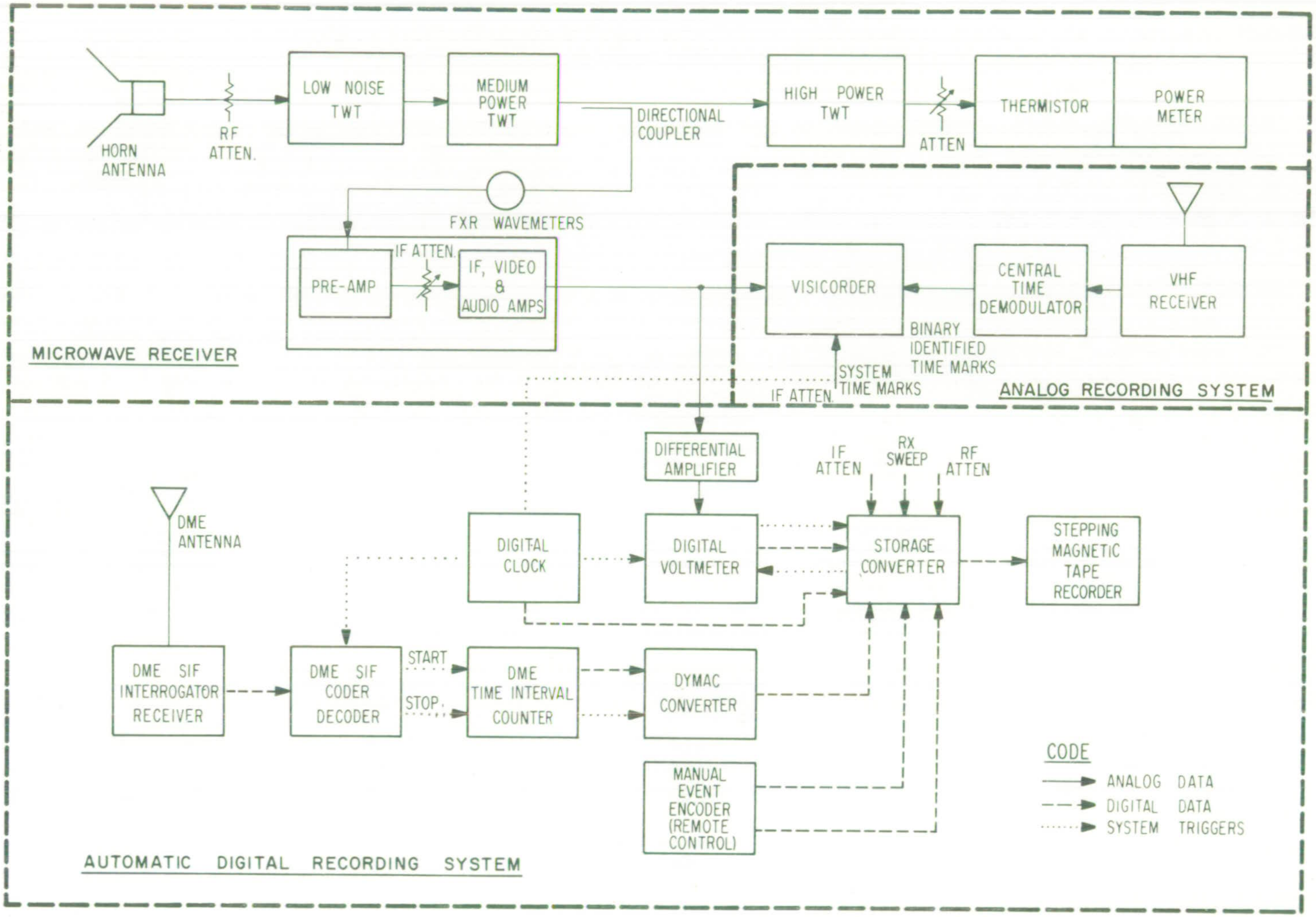

Figure 2. Block Diagram of Instrumentation

in the frequency band of interest. The power meter is also used to orient the antenna to receive maximum power.

A coaxial switch provides 10 or 20 db of RF attenuation ahead of the TWT's to prevent receiver saturation in the presence of very-high-power signals. The input to the TWT's may also be switched to a calibration noise source, a characteristic impedance load, or to a signal generator. The TWT's, antenna coaxial switch, and calibration noise sources are shown in Figure 3.

The output of the second TWT is applied to the preamplifier of a Polarad receiver through a directional coupler and FXR wavemeters. The absorption-type wavemeters provide a precise measurement ($\pm$ 0.25 MHz) of the frequency to which the Polarad is tuned. The Polarad is a triple-conversion superheterodyne receiver employing a klystron local oscillator. Rotation of the tuning dial simultaneously tracks double-tuned preselector cavities, the local oscillator, and the linear frequency dial. A separate tuning head is required for each frequency band. Image rejection of 60 db is obtained. The receiver bandwidth is 3.2 MHz for CW and the effective bandwidth is 6.5 MHz for a noise-type signal. A visual indication of the received signal is presented on a panel meter calibrated in decibels. Under normal operation, about 40 db of dynamic range is displayed. A recorder

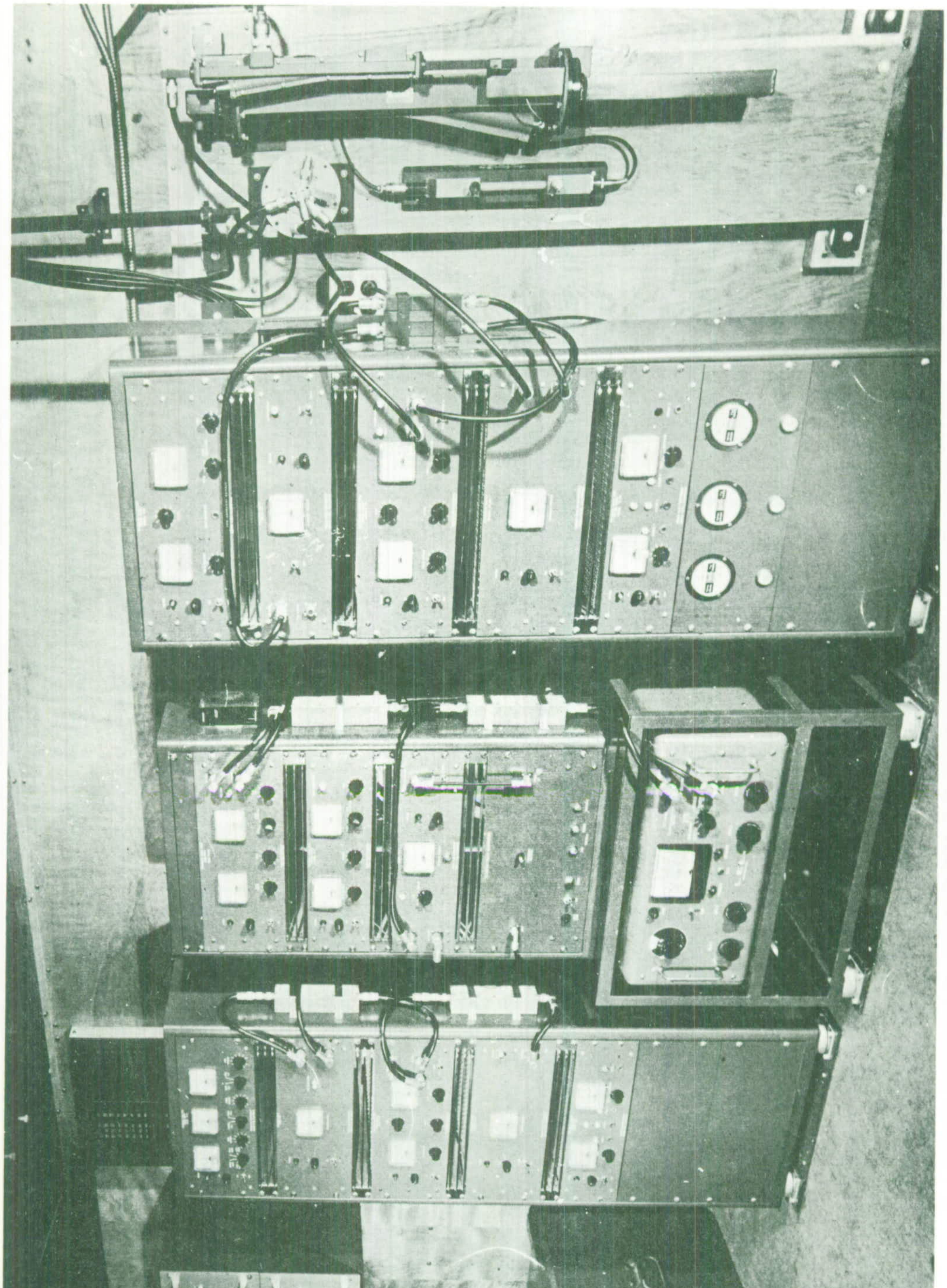

Figure 3. TWT's, Antenna Switch and Noise Sources

jack is available, in parallel with the output meter, from which the receiver output may be applied to both an analog recorder and an automatic digital recording system.

VHF step attenuators (1-, 5-, and 10-db steps) have been inserted in the lead from the preamplifier output to the input of the IF receiver. These are used to prevent receiver saturation and to increase the usable dynamic range when the receiver is operated with the AGC off.

ANALOG RECORDER

A Honeywell Visicorder, Model 1108, oscillograph paper-chart recorder is used to obtain an analog recording of the receiver output. The drive system which moves the paper may be mechanically coupled through a special gear box to the Polarad receiver to provide a recorded "spectrum" of the received signal. In the interferometer experiment, the receiver was tuned to a fixed frequency and the recorder was run continuously at a speed of a half inch per second.

The signal-recording galvanometer had a frequency response of 120 Hz. A DC level corresponding to the setting of the 5-db IF attenuator was also recorded by a second galvanometer. The system time marks generated by the digital clock were superimposed on the IF attenuator channel. Event marks, such as aircraft reported

position, minute marks, etc., were also recorded on this trace by manually depressing one of two available event buttons. A third high-frequency-response galvanometer was used to record the binary-identified central time one-second pulses, transmitted by PLER, to synchronize the phototheodolite camera operations. The oscillograph records, therefore, provided a complete record of signal characteristics, PLER time, monitor-van time, events, etc., with a relative accuracy of about 0.1 second, from which to correlate all experimental conditions.

AUTOMATIC DIGITAL RECORDING SYSTEM

An automatic digital recording system was designed to eliminate the tedious time-consuming task of manual data reduction required with an analog system. Data are recorded in digital form on half-inch magnetic tape in BCD (8, 4, 2, 1) code, which is immediately compatible with IBM digital computers. This system reduced the role of the analog system to that of a monitor and backup for correlating events occurring in separate areas of a particular mission. The system (block diagram included in Figure 2) was designed and constructed by Non-Linear Systems (NLS) to RCAF specifications.

The receiver output is fed to an NLS Differential Amplifier, Model 144, which has a fully floating input with an impedance of 100

megohms. The high common-mode rejection of the amplifier significantly decreases the effects of electrical noise.

An NLS Digital Voltmeter (DVM), Model 3209, performs the analog-to-digital conversion of the received signal within 400 milliseconds.

An NLS Digital Clock, Model DC6B2 (modified), provides time information and timing pulses for the system. The time base, with an accuracy of one second in a 24-hour period, is generated by a tuning fork oscillator.

The transfer of accumulated data to the magnetic-tape recorder is carried out by an NLS Storage Converter, Model 265M. Bit parallel information from the various data sources (28 characters in all) is converted into the standard BCD code and fed sequentially to the recorder at a rate of 100 steps per second.

The magnetic-tape recorder is a Digi-Data Model DSR-1400. It records, with a packing density of 200 bits per inch, on standard half-inch wide magnetic tape (reel diameter 10 1/2 inches). Up to eight hours of data may be recorded on a reel, at a sampling rate of one per second.

Provision has also been made, through the manual event encoder, to tape-record coded title information (date, mission number, frequency band, etc.), computer instructions (print titles, compute,

ignore, etc.), special events (aircraft range, altitude, etc.), and certain program constants.

DISTANCE MEASURING EQUIPMENT (DME)

The DME consists of a standard IFF/SIF interrogator (UPX-6 interrogator receiver and GPX-7 coder and decoder) and a time-interval counter (Hewlett-Packard counter, Model 5254L, with a Model 5262A plug-in time interval unit). A Dymac converter was required to convert the BCD 4, 4, 2, 1 output of the counter to a 10-line parallel input to the storage converter. The operation of the DME is discussed below in greater detail.

ANCILLARY EQUIPMENT

Dual VHF and UHF multichannel transceivers are available to provide communications between the monitor van and participating aircraft or control agencies that may be involved in a specific mission.

Hewlett-Packard signal generators are provided for each frequency band to calibrate the receiver output in terms of dbm at the input to the TWT's.

Noise sources are also used, in conjunction with a noise-figure meter, to obtain a measure of the system noise figure over each frequency band.

PRIMROSE LAKE EVALUATION RANGE (PLER)

The instrumented portion of PLER is situated on the south shore of Primrose Lake. The trials control center at PLER exercised close control of the participating aircraft with M33C radars. Target-aircraft positional information was fed to analog computers in the trials control center. The computers displayed the information on horizontal plotting tables equipped with dual pens for making simultaneous position plots of two aircraft. These plots were obtained as another backup to the primary range-measuring instrumentation (DME). The M33C data was also used to slave the phototheodolites situated along both shores of Primrose Lake within an area 10 miles long and 4 miles wide (phototheodolites are tracking telescopes with 35-mm recording cameras that provide accurate azimuth and elevation readings on airborne objects). All the phototheodolites were synchronized by the central time transmissions. Positional data was obtained from a digital computer using a common triangulation technique.

The phototheodolite data was presented in X, Y, Z, coordinates relative to a reference axis located within the PLER area. These positions were then referred to the monitor van to obtain slant range between the transmitter and the van site. This data was compared with DME ranges on all legs where phototheodolite data was available and was used to check the calibration of the DME.

The height component of the theodolite data was compared to radar-altimeter readings recorded in the transmitter aircraft and these measurements were used to correct the radar-altimeter data.

SECTION II

OPERATION AND CALIBRATING PROCEDURES

DISTANCE MEASURING EQUIPMENT (DME)

Pulses from the digital clock are supplied to a trigger generator, which, in turn, provides the triggers to the SIF coder. The coder generates a pulse pair for each input trigger to modulate the interrogator's transmitter. The pulses in the pair are separated by 3, 5, or 8 microseconds, depending on whether Mode I, II, or III is selected. The coder also produces a pulse used to start the time-interval unit counting the number of cycles of an internal 10-MHz precision oscillator. This pulse is delayed in time to partially compensate for the delays in the associated SIF equipment. The radio-frequency pulses from the interrogator are then transmitted on 1030 MHz to the airborne beacon, which, if adjusted to receive the transmitted mode, will, in turn, generate a series of pulses at 1090 MHz. When the beacon replies are received by the interrogator, they are detected and passed to the decoder. If the reply code is identical to the one set up in the decoder, a stop pulse is generated and fed to the time-interval unit to stop it counting. The stop signal is also the command signal for the time-interval unit to read out the range count into the monitor van's recording equipment.

There is a definite possibility that a reply may not be received to stop the counter, which would then continue counting into the next cycle until, finally, a stop pulse is generated. To prevent this undesirable occurrence, a second type of stop pulse is generated in the coder about 5 milliseconds after each start pulse. This second stop pulse is mixed in the decoder with the range stop pulse before being passed to the time-interval unit. If the range stop pulse is missing, the counter will stop at a range reading of 5 milliseconds (approximately 400 n. m.). The computer is programmed to ignore these readings in its calculations.

A second type of false range may occur when the transponder is interrogated by other ground interrogators, causing replies to arrive between the start time and the correct stop time. To eliminate this "running-rabbit" effect, the computer is programmed to compare the absolute difference between successive DME readings with a manually entered interpolation constant, which is derived from the aircraft radial velocity (in microseconds per second) relative to the ground receiver. Any deviations from this limit cause the last reading to be ignored.

OPERATION OF DIGITAL RECORDING SYSTEM

In a typical cycle of operation, the digital clock supplies a trigger to the DVM causing it to digitize the output of the microwave receiver. Upon completion of its scan, the DVM activates the storage

converter causing it to store all the data at its parallel inputs. The storage procedure requires about three milliseconds, after which a reset pulse is generated and fed back to the DVM, indicating that storage has been completed and serialization of the data on the magnetic tape has commenced.

The breakdown of a 28-character record by function is shown below.

Characters	Function
1-5	titles, identification, events
6	spare (always reads 0)
7-13	DME output (12.4 μsec $\simeq$ 1 n.m. slant range)
14	receiver sweep - indicates the setting of the receiver sweep-selector switch
15-20	digital clock time (hrs./min./sec., 24-hour clock)
21-22	interpolation constant; related to aircraft velocity and used by computer in checking validity of DME readings.
23-26	DVM reading (thousandths of volts)
27	RF attenuator - indicates the setting of the antenna coaxial switch which may be either Z_O, 0, 10, or 20 db
28	IF attenuator - indicates the setting of the 5-db step attenuator

A computer printout of a series of raw-data records is shown in Figure 4.

COMPUTER PROGRAM

Raw-data tapes are edited on an IBM 1401 computer before final processing on an IBM 7094. The editing program provides a method for correcting or eliminating any erroneous records; however, its primary function is to group the low-density raw-data records into blocks of 20 records each and to rerecord them at high density (556 bpi) for more efficient processing on the 7094.

The following events occur in the 7094 program:

(a) Title information and events are interpreted and printed out as headings for a particular mission

(b) The DME range entries are tested for validity and, if valid, the slant range is computed in feet and nautical miles

(c) DVM readings (signal level) are converted to calibrated power levels, using calibration tables supplied on data cards with the program.

(d) The settings of the RF and IF attenuators are converted to decibels and added to the amplitude. The computer printout (see sample in Figure 5) contains:

TAPE	DATA	.........10.........20.........30
365	365	3100000001596612574907525922
366	366	3100000001605612575007620922
367	367	3100000001612612575107701422
368	368	3100000001620612575207757622
369	369	3100000001626612575307792022
370	370	3100000001635612575407801122
371	371	3100000001642612575507803122
372	372	3100000001650612575607791522
373	373	3100000001656612575707750922
374	374	3100000001664612575807699522
375	375	3100000001673612575907633322
376	376	3100000001680612580007591822
377	377	3100000001685612580107560122
378	378	3100000001694612580207517822
379	379	3100000001701612580307466022
380	380	3100000001709612580407407422
381	381	3100000001719612580507344222
382	382	3100000001723612580607334921
383	383	3100000001732612580707386121
384	384	3100000001739612580807598120
385	385	3100000001746612580907476020
386	386	3100000001754612581007484920
387	387	3100000001762612581107614520
388	388	3100000001768612581207779720
389	389	3100000001776612581307486821
390	390	3100000001783612581407537022

Figure 4. Computer Printout of Raw Data Records

	TIME			RANGE		AMPLITUDE
	HR.	MIN.	SEC.	FT.	N.M.	DBM
0	12	57	38	74579.	12.274	-60.4
0	12	57	39	74923.	12.331	-61.1
0	12	57	40	75316.	12.395	-61.9
0	12	57	41	75759.	12.468	-63.0
0	12	57	42	76053.	12.517	-64.6
0	12	57	43	76447.	12.582	-67.1
0	12	57	44	76840.	12.646	-70.8
0	12	57	45	77184.	12.703	-76.1
0	12	57	46	77528.	12.760	-72.8
0	12	57	47	77872.	12.816	-68.7
0	12	57	48	78167.	12.865	-65.8
0	12	57	49	78561.	12.929	-63.6
0	12	57	50	79003.	13.002	-62.2
0	12	57	51	79347.	13.059	-61.0
0	12	57	52	79741.	13.124	-60.4
0	12	57	53	80036.	13.172	-59.9
0	12	57	54	80478.	13.245	-59.8
0	12	57	55	80822.	13.302	-59.8
0	12	57	56	81215.	13.366	-59.9
0	12	57	57	81510.	13.415	-60.5
0	12	57	58	81904.	13.480	-61.0
0	12	57	59	82346.	13.552	-62.0
0	12	58	0	82690.	13.609	-62.6
0	12	58	1	82936.	13.650	-63.1
0	12	58	2	83378.	13.722	-63.8
0	12	58	3	83723.	13.779	-64.6
0	12	58	4	84116.	13.844	-65.8
0	12	58	5	84607.	13.925	-67.2
0	12	58	6	84804.	13.957	-72.4
0	12	58	7	85247.	14.030	-71.3
0	12	58	8	85591.	14.086	-74.6
0	12	58	9	85935.	14.143	-76.5
0	12	58	10	86328.	14.208	-76.3
0	12	58	11	86721.	14.273	-74.3
0	12	58	12	87016.	14.321	-72.1
0	12	58	13	87410.	14.386	-69.2
0	12	58	14	87754.	14.442	-63.5
0	12	58	15	88098.	14.499	-66.1
0	12	58	16	88491.	14.564	-65.1
0	12	58	17	88934.	14.637	-64.3
0	12	58	18	89327.	14.701	-63.7
0	12	58	19	89671.	14.758	-63.0
0	12	58	20	90015.	14.815	-62.6
0	12	58	21	90359.	14.871	-62.2
0	12	58	22	90703.	14.928	-62.1
0	12	58	23	91097.	14.993	-61.9
0	12	58	24	91343.	15.033	-61.9

Figure 5. Sample of Computer Printout

- titles
- description of events
- time (hours, minutes, seconds)
- range in feet
- range in nautical miles
- signal amplitude in dbm
- an indication of whether the range was computed from a valid DME reading or interpolated from a crude plot of the signal amplitude versus time

RECEIVER CALIBRATION TECHNIQUES

In the multipath propagation measurements, the receiver was operated with the AGC off, so that rapid fluctuations in received-signal amplitude could be recorded. The following setup and calibration procedures were used:

(a) After 20 minutes warmup time, the Polarad dial was calibrated by manipulating the ZERO ADJUST and CALIBRATE GAIN controls.

(b) With the AGC off and the RF input to the low-noise TWT terminated into the characteristic-impedance load, the gain of the Polarad receiver was adjusted with the 1- and 10-db IF step attenuators so that the output meter read 30 db (midscale) on the 70-db meter range.

(c) The appropriate signal generator was connected to the input of the low-noise TWT and tuned to the selected calibrating frequency. The Polarad receiver was tuned to the signal-generator frequency.

(d) DVM readings and Visicorder signal-galvanometer deflections were recorded versus signal-generator power levels in dbm for various combinations of the RF and 5-db IF attenuators. The DVM readings versus signal-generator dbm were tabulated for one combination of the attenuators (normally 20 db RF plus 20 db IF) for use in the computer reduction of the digital records. The Visicorder deflections versus dbm were used to produce calibrated scales for manual reduction of the analog data, if required.

SECTION III

MEASUREMENT TECHNIQUES

The requirement for high measurement accuracy of transmitter range, height, and timing signals in this experiment was discussed in Volume I[1]. In this section the techniques used to achieve these accuracies are described in detail.

HEIGHT OF RECEIVER ANTENNAS

The height of the receiver antennas relative to the reflecting surface (Cold Lake) was required to an accuracy of ± 0.05 foot. A survey was carried out using a WILD NK 2-54903 level and a standard two-piece leveling rod between a spike driven into the Cold Lake pier and a solid steel shaft driven into the ground near the monitor-van site. This measure was repeated four times to within ± 0.01 foot. A graduated rod was fixed to the side of the pier to measure the level of the lake relative to the spike. This reading was checked periodically throughout the trial period and was found to be constant ± 0.03 foot. Finally, the height of the center of each antenna above the steel shaft was measured to within ± 0.01 foot. Between missions 106 and 107, the position of the van was changed slightly, necessitating remeasurement of the antenna heights. The following heights were obtained with a maximum error of ± 0.05 foot.

Band and Polarization	Missions 102-6	Missions 107-14
S-band horizontal polarization	58.90 ft.	59.49 ft.
S-band vertical polarization	58.94 ft.	59.53 ft.
L-band horizontal polarization	59.36 ft.	59.95 ft.

DME CALIBRATION AND ACCURACY

At the conclusion of the experimental missions, a special test was carried out to calibrate the accuracy of the distance-measuring equipment used throughout the trials as the primary source of range data on the signal-source aircraft.

The van was sited on the western shore of Primrose Lake at the most remote theodolite site. The position of the van in PLER coordinates was obtained from phototheodolite shots of the site. Central time transmissions were received in the van and used as the system trigger to minimize any time-correlation errors. The signal-source aircraft was flown as a test target on four legs radial to the van and passing through the center of the PLER phototheodolite coverage at 8600 feet above ground level (AGL). The APX-25 transponder was operated normally on the first two legs. On the second two legs, the APX-25 receiver sensitivity was reduced to low. Eighty additional legs were flown orthogonal to the original track and passing directly

over the active phototheodolites; the last four of these legs were flown at 100 feet AGL. Continuous phototheodolite and DME coverage was maintained throughout the flights.

The phototheodolite film was reduced at approximately 10-second intervals. The tail of the North Star aircraft was selected as the point at which film frames were read. The coordinates obtained were then corrected for the approximate location of the DME antenna position on the aircraft (50 feet forward of the extreme tail end). Using the coordinates of the van, also obtained from phototheodolite shots, the slant range (in feet) from the van to the aircraft was computed.

DME readings corresponding to the central times selected for phototheodolite reductions were obtained from a computer listing of the output tape from the automatic digital system, and were used to compute the slant range in feet. The combined results are presented in Table I.

The mean difference between phototheodolite ranges and DME ranges was calculated to be 105 feet, with a standard deviation of $\pm$ 35 feet. Subsequently, provision was made in the computer program to add 100 feet to the computed DME ranges.

The random error on DME readings is estimated to be an additional $\pm$ 50 feet ($\pm$ 1 count of the time interval counter). Therefore, the corrected DME readings have an overall maximum error of $\pm$ 50 feet (random), $\pm$ 35 feet (bias), or a total of $\pm$ 85 feet overall error.

Table I

Computer Listing of Time and Signal Aircraft Ranges

Aircraft Heading and Altitude	Central Time in Seconds	PLER Range R_1 (ft)	DME Range R_2 (ft)	$R_1 - R_2$ (ft)	Aircraft Heading and Altitude	Central Time in Seconds	PLER Range R_1 (ft)	DME Range R_2 (ft)	$R_1 - R_2$ (ft)
	564.82	8702	8691	11		2897.00	161860	161690	170
	574.82	9494	9450	44		3013.33	118680	118545	135
	584.82	11207	11114	93		3084.90	92146	92058	88
Radial	594.82	13503	13411	92	Radial	3157.84	65229	65140	89
Outbound	604.82	16116	15944	172	Inbound	3262.13	27455	27337	118
8600 ft AGL	614.82	18930	18828	102	8600 ft AGL	3272.13	23968	23890	78
APX-25	624.82	21861	21687	174	APX-25 Low	3282.13	20547	20413	134
Normal	634.82	24867	24793	74		3292.13	17255	17119	136
	644.82	27939	27816	123		3303.13	14194	14077	117
	732.83	55864	55786	78		3312.13	11513	11379	135
	809.30	80748	80666	82		3322.13	9610	9478	132
	881.24	104090	104011	79					
	953.02	127310	127236	74		3997.25	43652	43544	108
						4007.25	42614	42500	114
	1305.72	155650	155538	112	Orthogonal	4017.25	42444	42365	79
	1408.29	117460	117271	189	8600 ft AGL	4361.10	43163	43065	98
	1480.12	90946	90842	104	APX-25 Normal	4371.10	43337	43257	80
Radial	1552.32	64463	64371	92		4381.10	43885	43758	127
Inbound	1641.67	32066	31967	99		4391.10	44777	44650	127
8600 ft AGL	1651.67	28522	28395	127					
APX-25	1661.67	25030	24931	93		4782.55	44208	44100	108
Normal	1671.67	21576	21496	80	Orthogonal	4797.55	43221	43114	107
	1681.67	18277	18166	111	8600 ft AGL	5207.30	44498	44392	106
	1691.67	15155	15076	79	APX-25 Low	5222.30	45330	45209	121
	1701.67	12378	12254	124					
	1711.67	10253	10175	78		5977.20	44260	44146	114
	1721.67	9203	9150	53		5987.20	43893	43763	130

Table I (Cont.)

Aircraft Heading and Altitude	Central Time in Seconds	PLER Range R_1 (ft)	DME Range R_2 (ft)	$R_1 - R_2$ (ft)	Aircraft Heading and Altitude	Central Time in Seconds	PLER Range R_1 (ft)	DME Range R_2 (ft)	$R_1 - R_2$ (ft)
					Orthogonal	5997.20	43690	43606	84
	2133.78	9078	9054	24	100 ft AGL	6007.20	43712	43616	96
	2143.78	10539	10470	69	APX-25 Normal	6335.27	43922	43867	55
	2153.78	12716	12584	132		6345.27	43688	43557	131
Radial	2163.78	15294	15169	125		6365.27	43861	43768	93
Outbound	2173.78	18115	17981	134					
8600 ft AGL	2183.78	21045	20931	114		6678.80	44163	44048	115
APX-25 Low	2193.78	24077	23958	119		6688.80	43720	43606	114
	2203.78	27177	27066	111	Orthogonal	6698.80	43564	43458	106
	2213.78	30321	30173	148	100 ft AGL	6708.80	43688	43557	131
	2285.87	53567	53454	113	APX-25 Low	6965.53	43817	43704	113
	2358.40	77197	77048	149		6975.53	43544	43458	86
	2430.16	100787	100698	89		6995.53	43988	43875	113
	2502.40	124170	124075	95					

SIGNAL SOURCE ALTITUDE MEASUREMENT AND ACCURACY CONSIDERATIONS

The instrumentation used to measure the altitude of the signal-source aircraft consisted of three separate arrangements: radar altimeter mounted in the aircraft; the phototheodolite system at Primrose Lake; and the KS4 aerograph pressure-altimeter recordings.

The pilot maintained the aircraft at a constant pressure altitude according to the aircraft pressure altimeter, which provides resolution down to a few feet.

The radar altimeter could be used only while over the four large lakes along the track, and, because of the roughness of the terrain, only the height of the lakes above mean sea level could be determined accurately. At the start of each outbound leg, the radar altimeter was used to establish the nominal height, after which a constant pressure-altimeter altitude was maintained.

As the point of radar-altimeter signal reflection was always on the surface of Cold Lake, all altitudes were referred to that level. The heights of the other lakes above or below Cold Lake were used to modify the recorded radar-altimeter readings. Phototheodolite altitude coordinates were also modified by the height of Cold Lake above mean sea level. Both sets of data were plotted versus range; this is shown in Figure 6. Approximate range to the centers of the lakes from the van are:

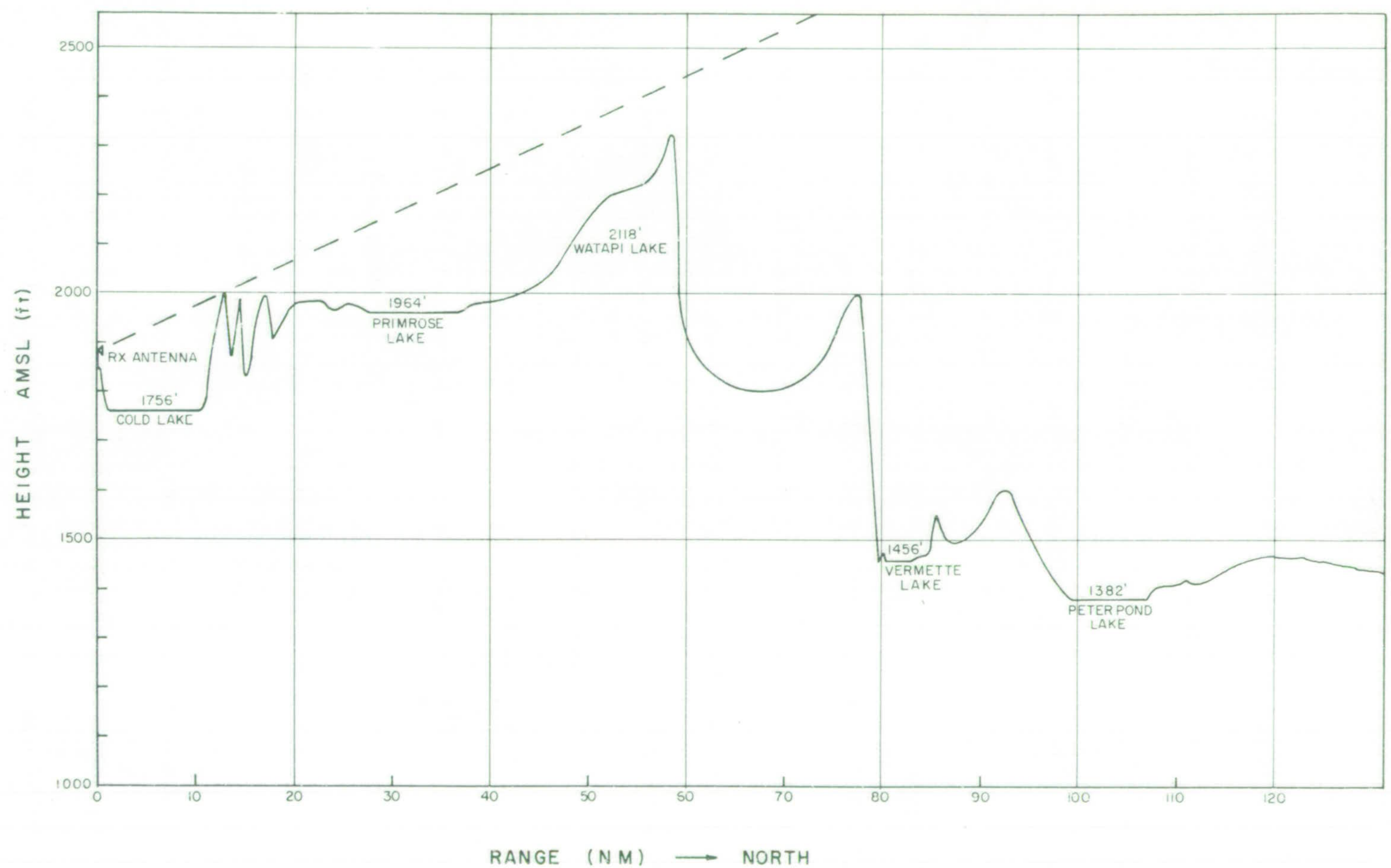

Figure 6. Topographical Profile of Test Area

Primrose Lake, 32 n. m. ; Vermette Lake, 81 n. m. ; and Peter Pond Lake, 105 n. m.

To obtain values of altitude versus range corresponding to the position of each fade in the interference pattern, an approximate best-fit straight line was drawn through the radar-altimeter data. The phototheodolite data available for ranges between 13 and 38 n. m. was used to derive corrections to the radar-altimeter data. It was discovered, statistically, that radar-altimeter readings were 62 feet higher than the theodolite readings within the limits of theodolite coverage, and had a standard deviation of $\pm$ 23 feet. In practice, the radar-altimeter data was tabulated in 25-foot increments from the best-fit straight line. The actual corrections applied (normally 50 or 75 feet) were selected to avoid interpolation between tables when determining values of A_e (effective earth radii) versus range.

The accuracy of the altitude determination was considered to be about $\pm$ 25 feet, based on the accuracy of theodolite data ($\pm$ 10 feet) and the accuracy of reading the radar altimeter (between $\pm$ 25 and $\pm$ 50 feet).

The altitude data from the KS4 aerograph system, while useful in establishing the approximate values of altitude and any radical variations in altitude, did not provide sufficient resolution to cast any

further light on the accuracy of either the phototheodolite or radar-altimeter data. The resolution was approximately 200 feet difference in altitude for 1/16-inch deflection on the recording paper.

RECEIVER FREQUENCY

At the beginning of the series of missions for each frequency band, the transmitter was centered on a preselected nominal frequency. The receiver was then tuned to receive the maximum signal. The frequency to which the receiver was tuned was then determined with FXR wavemeters. For all subsequent missions the receiver was tuned to this frequency and the transmitter was adjusted (prior to commencing each leg) until the maximum received signal was obtained. Transmitter-frequency drifts were monitored in the signal-source aircraft and corrected, if necessary, at the end of each leg. The accuracy of frequency determination was estimated to be better than $\pm$ 5 MHz on L-band and $\pm$ 10 MHz on S-band.

SECTION IV

DATA REDUCTION AND ANALYSIS

DETERMINATION OF THE POSITIONS OF SIGNAL MINIMA

The final objective of the interferometer experiment was to determine a value of effective earth's radius, A_e, corresponding to the range for each minimum in the interference pattern. The techniques used to derive the ranges for the minima are discussed below.

To obtain the best possible accuracy, the Visicorder records were used in conjunction with DME ranges from the automatic system. The time at which minima occurred could be read to $\pm$ 0.05 second (equal to $\pm$ 20 feet at the aircraft speeds involved). The DME readings versus time were plotted in the region of the observed fade and the exact range for the fade was then interpolated from the smoothed plot. Thus, the maximum error in this method was $\pm$ 85 feet (DME), $\pm$ 20 feet (TIME), or an accumulated error of $\pm$ 105 feet.

The computer printout of the digital recording system was used to check the accuracy of the above ranges for minima. Positions of minima could be determined to within $\pm$ 0.5 second from these printouts or a corresponding range error of $\pm$ 200 feet. Where the ranges differed by more than 0.03 n.m., the value obtained from the computer printout was entered in the second line of the range tables.

In some instances, normally at long ranges, the amplitudes of the minima were below the receiver noise level. In these cases, the first value recorded was the mid-position of the fade, as determined from the analog recordings, while the other values were the ranges for minimum computed amplitudes in the region of the fade, as taken from the computer printout.

EFFECTIVE EARTH RADII (A_e) DETERMINATIONS

A computer program was written to solve the equations from which the effective earth radii (A_e) were calculated as a function of transmitter range and height for each signal-fade time. Those equations are described in detail in Volume I. From the computer, a table of values was generated for D_n (range in nautical miles to transmitter), r_1 (distance to reflection point), and β (angle of incidence of reflected ray), corresponding to various combinations of the parameters h_1 (receiver height), h_2 (transmitter height), and λ (the radio wavelength).

Table II shows the range of D_n values corresponding to a particular fade from order $n = 1$ to order $n = 25$, and for A_e values from 3300 to 5900 n. m. In this case, h_1 was taken as 59.95 feet, h_2 as 4225 feet, and λ as 0.7125 foot. Of course, sets of such tables were available for all possible conditions experienced in the experiment

Table II

Computed Values of D_n

Tide = 0.0 H1 = 59.95 Lambda = 0.7125 H2 = 4225.0

A EFF n	3300.0	3500.0	3700.0	3900.0	4100.0	4300.0	4500.0	4700.0	4900.0	5100.0	5300.0	5500.0	5700.0	5900.0
1	51.48	52.56	53.59	54.58	55.53	56.43	57.30	58.14	58.95	59.72	60.47	61.20	61.90	62.58
2	39.26	39.83	40.36	40.86	41.33	41.77	42.19	42.58	42.96	43.32	43.66	43.98	44.29	44.59
3	30.99	31.29	31.58	31.84	32.08	32.31	32.52	32.72	32.91	33.08	33.25	33.41	33.55	33.69
4	25.25	25.43	25.59	25.74	25.87	26.00	26.12	26.22	26.32	26.42	26.51	26.59	26.67	26.74
5	21.16	21.26	21.36	21.45	21.53	21.60	21.67	21.74	21.80	21.85	21.90	21.95	22.00	22.04
6	18.13	18.20	18.26	18.31	18.37	18.41	18.46	18.50	18.53	18.57	18.60	18.63	18.66	18.68
7	15.82	15.86	15.91	15.94	15.98	16.01	16.04	16.07	16.09	16.11	16.13	16.15	16.17	16.19
8	14.01	14.04	14.07	14.10	14.12	14.14	14.16	14.18	14.20	14.22	14.23	14.24	14.26	14.27
9	12.56	12.58	12.61	12.62	12.64	12.66	12.67	12.69	12.70	12.71	12.72	12.73	12.74	12.75
10	11.38	11.39	11.41	11.42	11.44	11.45	11.46	11.47	11.48	11.49	11.49	11.50	11.51	11.51
11	10.39	10.40	10.42	10.43	10.44	10.45	10.45	10.46	10.47	10.48	10.48	10.49	10.49	10.50
12	9.56	9.57	9.58	9.59	9.60	9.60	9.61	9.62	9.62	9.63	9.63	9.63	9.64	9.64
13	8.85	8.86	8.87	8.87	8.88	8.88	8.89	8.89	8.90	8.90	8.91	8.91	8.91	8.62
14	8.24	8.24	8.25	8.25	8.26	8.26	8.27	8.27	8.28	8.28	8.28	8.28	8.29	8.29
15	7.70	7.71	7.71	7.72	7.72	7.72	7.73	7.73	7.73	7.74	7.74	7.74	7.74	7.74
16	7.23	7.24	7.24	7.24	7.25	7.25	7.25	7.26	7.26	7.26	7.26	7.26	7.27	7.27
17	6.81	6.82	6.82	6.82	6.83	6.83	6.83	6.83	6.84	6.84	6.84	6.84	6.84	6.84
18	6.44	6.45	6.45	6.45	6.45	6.46	6.46	6.46	6.46	6.46	6.46	6.47	6.47	6.47
19	6.11	6.11	6.11	6.12	6.12	6.12	6.12	6.12	6.13	6.13	6.13	6.13	6.13	6.13

Table II (Cont.)

A EFF n	3300.0	3500.0	3700.0	3900.0	4100.0	4300.0	4500.0	4700.0	4900.0	5100.0	5300.0	5500.0	5700.0	5900.0
20	5.81	5.81	5.81	5.81	5.82	5.82	5.82	5.82	5.82	5.82	5.82	5.83	5.83	5.83
21	5.54	5.54	5.54	5.54	5.54	5.54	5.55	5.55	5.55	5.55	5.55	5.55	5.55	5.55
22	5.29	5.29	5.29	5.29	5.29	5.29	5.30	5.30	5.30	5.30	5.30	5.30	5.30	5.30
23	5.06	5.06	5.06	5.06	5.06	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07	5.07
24	4.85	4.85	4.85	4.85	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86	4.86
25	4.66	4.66	4.66	4.66	4.66	4.66	4.66	4.67	4.67	4.67	4.67	4.67	4.67	4.67

and were used to determine the A_e values corresponding to a particular fade order n and transmitter range D_n. The complete set of tables is retained by The MITRE Corporation for further reference.

SECTION V

SUMMARY

Following an earlier test at Cold Lake [2] it became evident that data should be recorded automatically in digital format at the van site. In this way large quantities of information could be assimilated for later processing with computers. Also by recording signal source range from the van site the dependence on phototheodolite data is thereby circumvented.

The monitor van facility described herein met the requirements for the collection and assimilation of large quantities of data and with a high degree of accuracy.

Based on a comparison of meteorological and interferometer data it appears that the monitor van facility could be used, possibly in real time, to obtain meaningful information about the effective radio propagation conditions. To complete an operational system it would be necessary to obtain signal source height data in real time and arrange a direct input of all information to associated computational facilities. It also appears that by using two vertically spaced antennas one could eliminate the water reflection aspect of the existing facility and with considerable advantage when the water surface may be moving due to tidal oscillations.

Although a comprehensive analysis of such a system has not yet been made, the Cold Lake experiment certainly indicates that the vertical interferometer technique could provide a great deal of information about the effective propagation conditions. It has the great advantage of possibly circumventing the requirement for direct meteorological measurements, where in many instances it is not economically feasible to locate surface-based radiosonde launch sites.

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2. L. G. Rowlandson, Radio Ray Bending in the Lower Troposphere Measured with a Reflection Interferometer, The MITRE Corporation, ESD-TR-67-102, March 1967.

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13. ABSTRACT

A radio reflection interferometer was used to determine effective earth's radii values from the observation of multipath fading records and corresponding signal source positions. Received signal levels, master timing codes, and signal source range were automatically recorded in digital and analog format. Signal source height was obtained from radar altimeter and phototheodolite records.

The digital and analog data were processed in an IBM 7094 to obtain extremely accurate calculations of the propagation parameters.

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